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On Detecting a Hard Target in Chaff

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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ON DETECTING A HARD TARGET IN CHAFF.

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ON DETECTING A HARD TARGET IN CHAFF

I. INTRODUCTION

Chaff plays an important role in U.S. penetration systems currently in use and being planned. Its purpose is to produce a clutter signal, in nature similar to noise, in a radar receiver that will mask the desired signal from the hard target, be it a re-entry vehicle or decoy. The degree of masking is ordinarily characterized by the received S/N (or signal-to-noise, i.e., chaff, ratio) generally expressed in db, which is the difference between the scattering cross section of the body and that of the interfering chaff. Frequently however a considerable improvement in this S/N can be achieved by appropriate modulation design and signal processing. Some of these techniques are familiar to the radar community, but apparently not so well known to other potential users.

It is the purpose of this report to offer a brief exposition of some of the principles by which this S/N improvement can be obtained. It should be mentioned that the methods of enhancing a desired signal stem from radar detection theory and information theory and apply as well to forms of interference with characteristics similar to those of chaff, such as true radio or receiver noise, clutter and noise jamming. This document is restricted to a rather qualitative description of such methods, and does not delve into the refinements of optimal solutions found in information theory to maximize the S/N enhancement.

II. DISCUSSION OF THE METHODS

The basic principle of improving S/N can be stated very simply: Differences in the spatial and spectral characteristics between the signal returned from the hard target and that from the interference (chaff returns, noise jamming, etc.) are exploited to reduce the latter relative to the former. To illustrate the principles with specific examples, it is assumed, unless otherwise noted, that the signals are being sampled at a regular interval τ, i.e., by a radar with prf = $1/\tau$, and that the interference has the characteristics of a gaussian noise. It might be noted that the unresolved return from as few as four or five randomly moving targets, such as chaff dipoles, is a reasonable approximation to gaussian noise. It is also assumed that the clutter has no preferred polarization or that the radar has already taken advantage of any gain available on this account.

A. Spatial distribution

A hard body (re-entry vehicle or decoy) is spatially a point target to any radar with a bandwidth less than about 30 Mc (even for the longest vehicles), while the clutter is almost always an extended target compared with the pulse length. Suppose the spatial target distribution is represented by Figure 1,

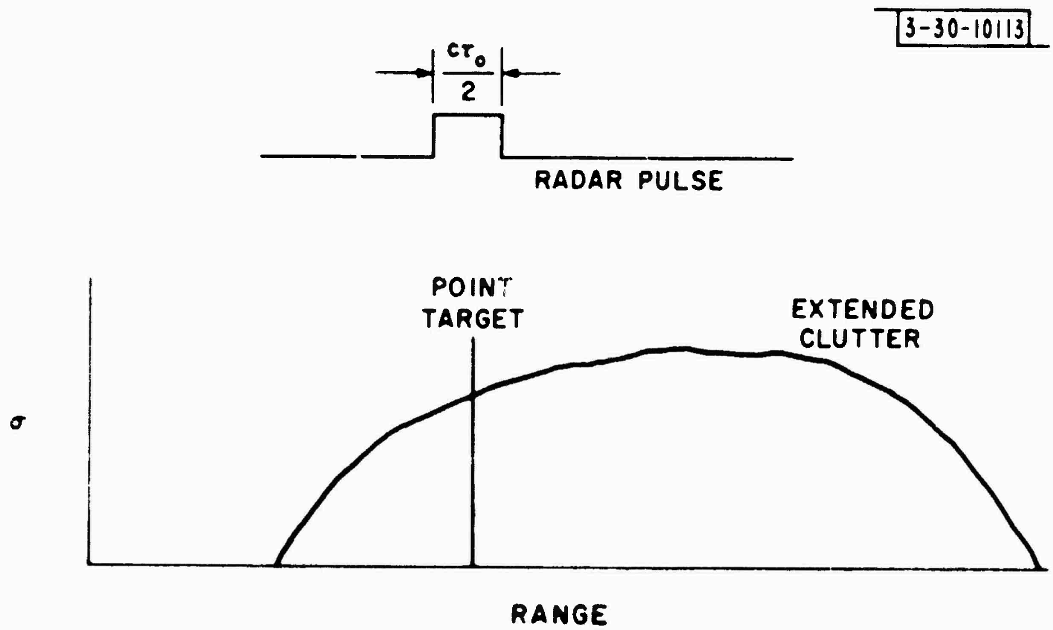

Figure 1: Schematic illustration of point target in spatially extended clutter.

where the spike represents the hard target with a cross section σ_B. If the radar pulse length is L (= 150 τ_o meters, where τ_o is the pulse duration in microseconds), then the interfering signal cross section is $\sigma_C'L$, where σ_C' is the clutter (chaff) cross section per unit length in the vicinity of the body, and the single-pulse signal-to-noise ratio is $S/N = \sigma_B/\sigma_C'L$. Purely from the standpoint of single-pulse detection, the shorter the pulse, the higher S/N. Greatly decreasing the pulse length however has the practical disadvantages of lowering sensitivity to the point where system noise may predominate over the signals being discussed and requiring more data processing. In addition, the pulse length may be related to the spectral properties of the chaff return, as will be discussed below.

A comment on range ambiguity is appropriate at this point. An apparent radar range is ambiguous to a multiple of the distance determined by the interpulse spacing or prf. The range ambiguity is 150 km for a prf of 1000 per sec, and varies inversely as the prf. Clutter from ranges differing from the true range of the target by a multiple of this ambiguous range is not resolved from that at the true range of the target, thereby decreasing the expected single-pulse S/N. This situation could arise in radars with high prf for long chaff distributions, and could be helped in such a case by decreasing the prf. However, the loss of sensitivity and serious consequences to the spectral capability of the radar generally limit application of this measure.

These effects on S/N, produced by changing the signal design and processing to take advantage of the difference in spatial characteristics between the desired return and the clutter, seem quite straightforward, even trivial; yet the techniques to be considered in the remaining sections are nothing more than an application of these same ideas to the frequency, rather than spatial, domain.

B. Separation in doppler frequency

The frequency spectrum of the radar return may be examined by Fourier-analyzing a section of the signal. There are two significant parameters that determine the measurement capability in the sample spectrum. The maximum frequency that can be measured unambiguously is found from sampling theory to be equal to the prf ($= 1/\tau$) for coherent radars (that measure both amplitude and phase) and half the prf for incoherent radars (amplitude only). Higher frequencies are translated into this range at an aliased frequency, indistinguishable from a spectral component truly at that frequency. The other relevant parameter is the frequency resolution, which is equal to the reciprocal of the sample duration, or integration time, chosen for the spectral analysis. The stated resolution is a nominal one, valid for defining the detail observable in a continuous spectrum, but the fixed doppler frequency returned from a point target moving at constant radial velocity may be found to considerably greater accuracy, just, for example, as the range of a point target can be found more accurately than the nominal range resolution.

The doppler velocity, v_d, corresponding to a stated doppler frequency, f, is given by the expression $v_d = \frac{c}{2}\frac{f}{f_R} = \frac{\lambda f}{2}$, where f_R is the radar frequency and λ its wavelength. For example, the maximum unambiguous velocity measured by a coherent radar at 1500 Mc (λ = 0.2 m) with a prf = 10^5 sec^{-1} (τ = 10 μsec) is 10^4 m/sec, greater than full re-entry velocity, that for a coherent radar at 500 Mc (λ = 0.6 m) with a prf = 1500 sec^{-1} is 450 m/sec, adequate for many wake and chaff spectra, and that for an incoherent radar at 5000 Mc with a prf = 100 sec^{-1} is 1.5 m/sec, inadequate for almost any application. The nominal resolution for the 500-Mc radar integrating for T = 0.1 sec (substitute $f = \frac{1}{T}$ in the formula) is 3 m/sec, while that for the 1500-Mc radar integrating for 500 μsec is 200 m/sec. Radar capabilities for detecting and resolving hard targets in chaff are obviously greatly affected by the parameters just described.

The simplest situation in which great gain in S/N can be achieved from spectral analysis occurs when the mean velocity of the chaff (clutter) is different from that of the colocated hard target, as illustrated in Figure 2. The velocity separation may arise exoatmospherically if the chaff is dispensed from a point separated spatially from the body it is intended to cover, and a velocity separation inevitably develops during early

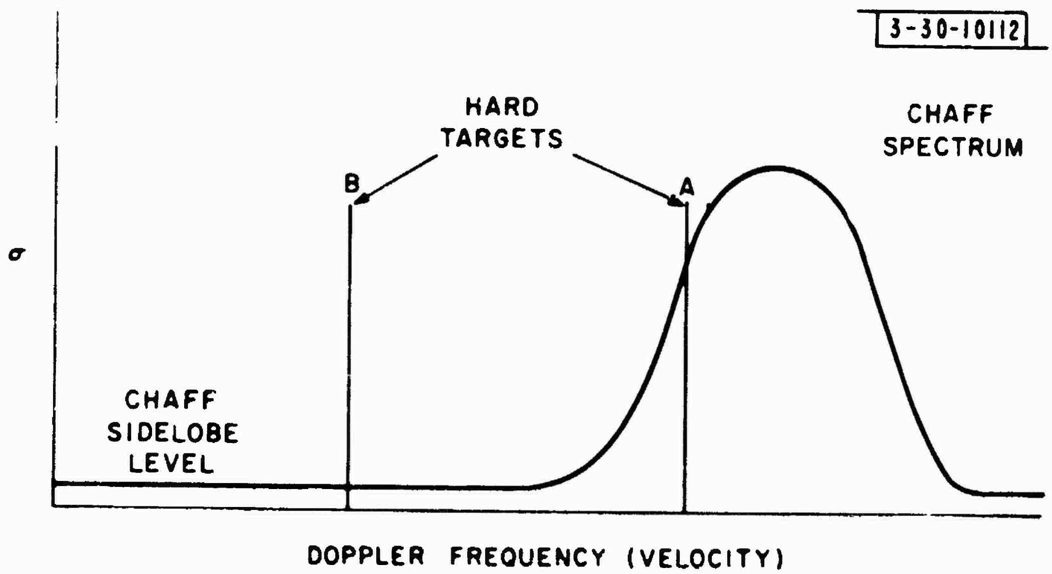

Figure 2: Illustration of hard target separated in velocity from mean chaff velocity, A) by a difference comparable to the velocity spread of the chaff; B) by a difference much larger than the chaff velocity spread.

re-entry due to the slowdown of the low-β chaff. Case A in Figure 2 shows the hard target off to the side in the main chaff velocity distribution. The gain in S/N over that for no velocity separation clearly depends on the chaff velocity distribution, the actual separation and the velocity resolution (to be discussed further in the next section). The extreme case of separation is illustrated by case B, where S/N is limited only by the chaff sidelobes resulting from the spectral processing that may typically be of the order of 30 db below the chaff peak. It can be seen that a quantitative estimate of S/N advantage to be gained from a velocity separation requires considerable information on the particular circumstances.

C. Difference in spectral width

It will now be assumed that no separation exists between the body velocity and the mean chaff velocity at the same range. This situation is illustrated in Figure 3, where a spectral width is indicated both for the body, Δf_B, and for the chaff, Δf_C. The gain achievable in S/N is clearer in the case of such a spectral width difference than it was in the previous section. For example, if the ratio of body-to-chaff cross section is unity (0 db), this is equivalent to the areas under the two curves in Figure 3 being equal. It is apparent then that the actual S/N at the center frequency is about $\Delta f_C / \Delta f_B$. This gain can be realized in general by examining the spectral plot similar to

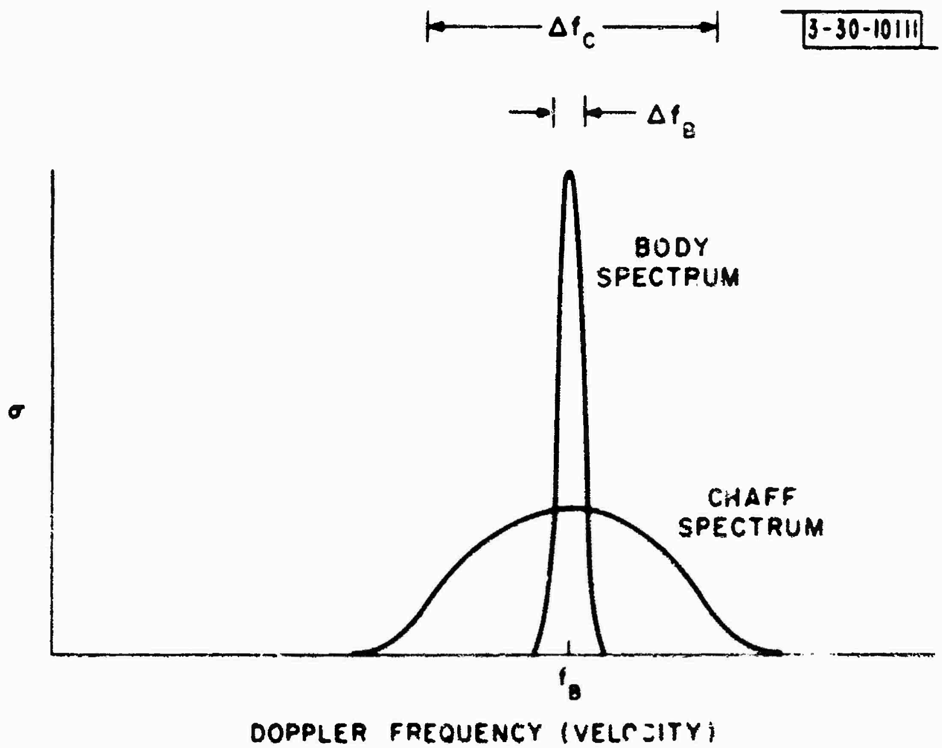

Figure 3: Doppler spectra of a hard target and chaff with no separation of mean velocity.

Figure 3 or, if the parameters are known, simply by passing the returned signal through a filter of bandwidth Δf_B centered at f_B, the body doppler (center) frequency.

To obtain an approximate value for the increase in S/N, estimates are required of the two spectral widths to be expected. For the case of a body that is not highly stable in spatial orientation, the return fluctuates due to the changing aspect presented to the radar. The bandwidth Δf_B is then approximately the frequency with which lobes in the body scattering function sweep by the radar, which in turn depends on details of the motion as well as on the radar frequency. For example, an RV of 2-m length tumbling end-over-end every 6 sec would result in a width $\Delta f_B \approx 1$ cps at UHF, this figure being approximately proportional to frequency. Bodies that are executing some less violent motion would exhibit a bandwidth a few times narrower, and bodies that are well stabilized might exhibit a very narrow bandwidth indeed.

The bandwidth of the chaff return also depends on the dynamic motion of the chaff cloud. The tumbling frequency of the individual dipoles places a lower limit, probably a very few cps, on Δf_C, but the changing configuration of the dipoles relative to each other may well increase this figure. A lower limit on Δf_C based on this mechanism may be obtained by considering the growth rate of the cloud. To illustrate, assume a dispensing velocity of

$\pm v_o$ m/sec. After t sec, the cloud will have grown to a diameter of $2v_o t$ m and will have a velocity gradient of $\frac{2v_o}{2v_o t} = \frac{1}{t}$ m/sec/m. Thus a pulse of duration τ_o with a range resolution $c\tau_o/2$ will in one range cell detect a velocity spread along the range axis of $c\tau_o/2t$ (note that this quantity is proportional to pulse length and independent of dispensing velocity). As an example, this velocity spread for a 1-μsec pulse observing a cloud 500 sec after dispensing would be 150m/500 sec = 0.3 m/sec, which at UHF corresponds to a frequency spread of about 1 cps. More generally, the velocity spread observed by the radar includes the variation lateral to the range direction, which may be much larger than the lower limit just calculated, particularly for extensive clouds, but which requires detailed trajectory analysis for a quantitative estimate. Actual field observations of chaff scintillations in a large cloud indicate a bandwidth at UHF of the order of 30 cps. This higher bandwidth is presumably due to the lateral variations, and would therefore not be very sensitive to pulse length. It would be most interesting to see, both by calculation and field measurement, this bandwidth decrease for small chaff puffs.

The result of these two calculations of scintillation bandwidth is the ratio giving the gain obtainable by coherent integration, as described at the beginning of this section. The possible values range from very little gain, that would appear to be possible for a not-highly-stabilized body in a small chaff puff, to 15 db or more for a target in an extended chaff cloud. Since both numerator and denominator are proportional to radar frequency, the result should not be sensitive to the frequency (although individual parameters, such as processing filter bandwidths, do of course depend on frequency).

An alternative and frequently useful approach to the problem being considered is to examine the data directly in the time domain. The results of course are equivalent. It is well known that coherent samples add in amplitude; incoherent, i.e., uncorrelated, samples add in power. Thus the signal power for n coherent samples is n^2 times the individual power, the noise power just n times, and the resulting S/N is therefore n times the single-sample value. Crudely speaking, a signal may be considered coherent for its correlation time, which is about the reciprocal of its spectral width. For the spectra shown in Figure 3, pulses that are returned in an interval $1/\Delta f_C$ are effectively coherent for both hard target and chaff, so no gain over the single-pulse S/N is achieved by integration over that period. (This point will be taken up again in the next section.) Since each period of duration $1/\Delta f_C$ contributes just one uncorrelated sample, the gain in S/N over the period $1/\Delta f_B$ is given by $n = \Delta f_C/\Delta f_B$, as before. Integration beyond the interval $1/\Delta f_B$ yields no further gain, since the body signal is then effectively incoherent. (It is assumed that the radar is not so highly sophisticated that it can specify the body return, which is after all not random but determinate, and then synthesize a matched filter to achieve coherent integration over much longer periods.)

The foregoing discussion also has an implication for the case wherein the radar prf is less than Δf_C. This is an unlikely case for chaff, but much more likely for noise jamming, for which the bandwidth of the jamming signal, even if it is tuned to the radar frequency, may be considerably greater than the prf. In this situation, the clutter samples are all uncorrelated and the coherent integration yields a gain in S/N simply equal to the total number of pulses over which the body return is coherent. (The equivalent description in frequency space involves overlap of ambiguous frequencies, which degrades the nominal gain of the bandwidth ratio down to the aforementioned number of pulses.) To illustrate, coherent integration for a target over a 1-sec period gives a S/N gain of 20 db for a prf of 100 and 30 db for a prf of 1000 against a wide-band source of clutter, such as a noise jammer.

It should be mentioned in passing that some integration gain can be attained even with incoherent radars, though not so much as with coherent radars. For example, if it is expected that a number of adjacent range cells have equal clutter in them, but that one of them also contains a body of constant cross section, then square-law detection and integration after the manner of a radiometer will give a gain in S/N proportional to $\sqrt{n}$, rather than n as in the coherent case.

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D. Variation of radio frequency

For the normally found chaff condition studied in the previous section, it was observed that no gain over the single-pulse S/N was obtained by integrating over all the pulses in an interval $1/\Delta f_C$, the chaff correlation time. It would of course be most desirable (for the defense) to utilize all of the radar pulses to increase S/N, which would occur if the signal from the clutter or chaff were uncorrelated on all the sampling pulses. One manner of accomplishing some such decorrelation is to take advantage of the change in scattering properties with radio frequency that results from the different spatial extents of hard target and clutter.

Crudely speaking, the scattering cross section of a configuration of scatterers, particularly a random distribution of scatterers, becomes decorrelated when the radio frequency is changed so that another one-half wavelength is included in the range extent of the configuration. For a 1-μsec radar, the 150-m range resolution implies a change in radio frequency of 1 Mc; a 0.1-μsec radar requires a 10 Mc shift. In other words, the range resolution cell naturally selected by a radar with a given bandwidth requires a shift of just that bandwidth to decorrelate the return from a random distribution of scatterers.

This phenomenon can be applied to the current problem, at least in principle, by contemplating a radar that jumps in frequency by its own bandwidth with each successive pulse so as to

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produce uncorrelated clutter returns while leaving the much shorter body with a coherent return. The process can be continued until the radar frequency is changed so much that the body return becomes decorrelated. It is clear that the number of pulses required to do this is approximately the ratio of the length of the range resolution cell to the length of the hard target. If during the time required to transmit these pulses the clutter returns that would be obtained at constant frequency have not yet decorrelated, then the coherently integrated S/N is increased further by the range ratio just described. If the clutter returns at a given frequency are decorrelated in this time, then of course the individual clutter returns can all be made incoherent in fewer jumps.

To illustrate what may be possible, consider the case of a 1-μsec radar with a prf of 1500 sec^{-1} that observes a body 2 m long with a coherence time of 1 sec in a chaff cloud scintillating at 30 cps. The range ratio of 150/2 = 75 allows 75 successive 1-Mc shifts in frequency, all of which give uncorrelated chaff returns. These pulses would occupy 1/20 sec, more than enough to decorrelate the chaff return by its own motion, so that the cycle can be restarted. The result is that in the available 1 sec of integration time all 1500 pulses are used to increase the body observability in chaff, in this case by 32 db.

It might be pointed out that in some circumstances the radar pulse length does not strongly affect S/N. In the example where the spectral width was dominated by lateral velocity gradients, the range resolution had little effect on the spectrum. If the assumed 1-μsec pulse were changed to 0.1-μsec, the single-pulse S/N would be increased by a factor of 10 simply because of the smaller quantity of chaff in the resolution cell, but the possibility of decorrelating by frequency shifting is reduced by a factor of 10, thus rendering the situation bandwidth-insensitive. This result should not be surprising, since the frequency jumps in effect synthesize for the present purposes a signal of the total bandwidth used, but without requiring the instantaneous radar bandwidth to be that wide.

III. CONCLUSIONS

It has been seen that by using the technique of coherent integration to take advantage of differences in the scattering characteristics between hard targets and chaff (or other interference), it is possible to achieve some gain over the single-pulse signal-to-noise ratio. Depending on the circumstances (chaff distributions, body characteristics and radar parameters) this gain might range from relatively modest amounts to 30 db or more. Determination of the gain for a particular set of conditions requires detailed calculations appropriate to those conditions, which may in turn serve as a guide for offense and defense planners to improve the operation of their systems.